Title: "A CONTROL SYSTEM FOR CONTROLLING THE MOVEMENT OF A PISTON IN A FLUID-PUMPING DEVICE, A METHOD OF CONTROLLING THE MOVEMENT OF A PISTON IN A FUID-PUMPING DEVICE AND A FLUID-PUMPING DEVICE"

The present invention relates to fluid-pumping devices such as, for example, linear compressors and, particularly, to a system and a method for controlling this kind of device, being driven by a linear electric motor.

Description of the Prior Art

A linear motor is an ancient idea, but it was carried out only recently with maturation in the field of control and actuation of electric machines. A linear motor replaces rotary electric motors with many advantages, among which the economy of electric energy, since it used a more direct conversion of electric energy with less loss. Especially the use of linear compressors in present-day cooling cycles has been scarce due to the technologic difficulties usually encountered.

The configurations of a linear motor and of a linear compressor may vary; the latter may be of simple or double effect, while the motor may comprise a work coil and a magnet; and this magnet may be either moveable or static.

In the case of the linear compressor in question, one has opted for the simple effect, a fixed coil and a moveable magnet.

Linear-type compressors are known from the prior art and are constituted by a mechanism in which the piston makes an oscillatory movement, and in most cases there is an elastic means interconnecting the cylinder and the piston, which imparts a resonant characteristic to this movement the energy being supplied by a linear-displacement motor. Equivalents such as piston-actuated water pumps or any fluid-pumping device can benefit from the object of the present invention.

In any case, in order to prevent the piston from moving past the desired amplitude, which might cause damage to the valve plate, the movement of said piston should be controlled.

A solution for controlling the movement of the piston is described In document US 5,704,711, in which the piston stroke is primarily proportional to the voltage level imposed on the linear motor, which is of the fixed-magnet and moveable-coil type. In this solution the mechanism is constructed in such a way, that the ratio between piston stroke and piston diameter is great, which causes the variation of the end position reached by the piston during its oscillatory movement, due to the variations in feed voltage and load, not to interfere significantly with the characteristics of effectiveness and capacity of the compressor cooling.

In this solution the mechanism is provided with a discharge valve constructed in such a way, that, if the piston exceeds the maximum displacement course expected in its oscillatory movement, for instance when the voltage imposed on the motor is excessive, there will be contact of the piston with this discharge valve, and this valve will allow the piston to advance a little, thus preventing an impact against the plate of the valve head.

Another known solution is described in document US 4,602,174, where the course of displacement of the piston is also primary proportional to the voltage imposed on the linear motor, which is of the moveable-magnet and fixed-coil type.

In this solution the design of the mechanism does not allow the piston to advance past a determined point; otherwise, the piston would collide with the valve plate. Due to the search for a more optimized design, as far as efficiency is concerned, the ratio between the course of displacement of the piston and the diameter of the piston is not great, which makes the performance of the compressor more dependent upon the variations in the course of displacement of the piston. As an example, the gas-discharge process gives a very small option of the course, namely about 5% of the total.

Another effect that occurs with this type of compressor is the displacement of the middle point of the oscillatory movement, whereby the piston is moved away from the discharge valve. This is because of the elastic deformation of the resonant mechanical system, formed by the piston and by a spring, when there is a difference in pressure between the two sides of the

piston. This deviation from the middle point of the oscillatory movement is proportional to the difference in pressure between the discharge and the suction.

For the above reasons, in this situation, it is necessary to control the course of displacement of the piston, by means of a device that controls the voltage imposed on the linear motor, re-fed by the information of piston position, basically estimated on the basis of the information about the current supplied to the motor and the voltage induced in the motor terminals. Solutions like this are described in documents US 5,342,176, US 5,496,153, US 5,450,521, and US 5,592,073.

One of these solutions can be found in document EP 0 483 447 which discloses a system that controls the duty cycle in pulse with modulated voltage applied to electric motors. This system is configured to regulate the piston's movement to operate at constant amplitude, by generating a train of rectangular voltage waves which are in inverse proportionality to the supplied voltage. The avoidance of collisions of the piston in this solution is not effective.

Another solution for controlling the movement of the piston is described in document PI 9907432-0. According to the solution described therein, a monitoring system is foreseen for monitoring the times the piston passes by a determined reference point within the compressor. In this way, when the residence time of said piston beyond the reference point exceeds a pre-established value, the voltage level is momentarily reduced during the respective movement, thus avoiding a collision with the valve plate.

Further according to another technique described in document JP 11336661, the movement of the piston is controlled by counting discrete points thereof along the cylinder of the compressor. In case the piston moves excessively, the value of the average voltage applied to the respective motor is reduced so as to decrease the movement amplitude of said piston.

Another way adopted to provide re-feeding to this voltage controller is to observe whether the piston collides with the valve plate. Such a collision is detected by means of a microphone or accelerometer, which gen-

erates a command for reducing the voltage applied to the motor and consequently the course of displacement of the piston.

Objectives of the Invention

The objective of the invention is to control stroke course of displacement of the piston of a linear compressor or of any fluid-pumping device, such as piston-actuated water pumps, allowing the piston to advance as far as the end of its mechanical course of displacement, even in extreme load conditions, without allowing the piston to collide with the valve system.

It is also an objective of the present invention to control the course of displacement of the piston of a linear compressor or of any fluid-pumping device, allowing the piston to advance as far as the end of its mechanical course of displacement, even in extreme load conditions, without allowing the piston to collide with the valve system, even in the presence of external disturbances of the power-feeding network.

Another objective of the present invention is to provide control over the course of displacement of the piston of a linear compressor or any other fluid-pumping device, without the need for information about the displacement of the middle point of oscillation of the piston.

A further objective is to provide control over the amplitude of the course of oscillation of a linear compressor or any fluid-pumping device, allowing control over the cooling capacity developed by the compressor.

Also other objectives of the present invention are to obtain a control system that meets the objectives of the present invention, that is easy to implement on an industrial scale and that has a low unit cost of manufacture and replacement, and to obtain a system that is self-fed, dispensing with the use of an additional external source, and that still has a low consumption of electric energy.

Brief Description of the Invention

In order to achieve the objectives of the present invention, a control system is foreseen for controlling the movement of a piston in a fluid-pumping device, the piston being displaceable in a block of the fluid-pumping device and being driven by a motor fed by a voltage. The system comprises

a semiconductor electronic device having an outlet and an inlet, the semiconductor electric device cyclically applying the voltage to the motor for driving the piston, a resistive element, a capacitive element, a piston-position sensor for indicating the passage of the piston by a point at the block of the fluid-pumping device, the capacitive element being electrically connected to the semiconductor device between and re-feeding the outlet and the inlet, the capacitive element triggering the semiconductor electronic device to apply the voltage to the motor; the capacitive element being charged by means of the resistive element at each cycle of application of voltage to the motor, the capacitive element being discharged at least partly when the piston passes by said point.

Further according to the present invention, the objectives are achieved by a method of controlling the movement of a piston in a fluid-pumping device, the piston being displaceable in a fluid-pumping device and being driven by a motor fed by a voltage. This method comprises the steps of: charging a capacitive element by means of a resistive element; monitoring the movement of the piston by means of a position sensor; maintaining the charge level of the capacitive element until the position sensor has detected the passage of the piston by a predetermined point at the compressor block; and discharging the capacitive element at least partly.

Further according to the teachings of the present invention, these objectives are achieved by means of a fluid-pumping device comprising a piston displaceable in a block, the piston being driven by a motor fed by a voltage. This device comprises a circuit having a semiconductor electronic device, a resistive element, a capacitive element, a piston-position sensor for indicating the passage of the piston by a point at the compressor block. The resistive element and the capacitive element are electrically connected to the semiconductor electronic device, re-feeding an outlet and an inlet of the latter, the capacitive element being charged by means of the resistive element and being discharged at least partly when the piston passes by said point.

Brief Description of the Drawings

The present invention will now be described in greater detail with

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reference to one of the embodiments represented in the figures, in which

- Figure 1 shows a linear compressor schematically;

- Figure 2 illustrates the curves of piston displacement and the voltage on the linear motor provided with the control system of the present invention;

- Figure 3 illustrates a control system for controlling the position of the piston of a linear compressor according to a first embodiment of the present invention; and

- Figure 4 illustrates a control system for controlling the position of the piston of a linear compressor according to a second embodiment of the present invention;

- Figure 5 illustrates the behavior of the signals generated by the bidirectional start switch and the time relationship of these signals with the voltage of the circuit branch that contains the capacitor Cy.

Detailed Description of the Figures

As can be seen in figure 1, a linear compressor 1 basically comprises a piston 10 that is displaced in oscillatory motion within the block 5, so as to compress a gas that is charged and discharged through a valve plate 11, which comprises a charge valve 13 and a discharge valve 12.

Typically, an elastic means such as a spring 4 is associated with the piston 10, so that the latter can have a resonant movement within the block 5 of the compressor 1.

The movement of the piston 10 is induced by a linear-type motor 2, which in turn is driven by an electric voltage V, which should be controlled in order to prevent the piston 10 from colliding with the plate 11.

Although the figures illustrate a linear compressor, the object of the present invention is applicable to any fluid-pumping device 1, as for example a water pump. For this purpose, one should only to take into consideration the constructive differences between such devices.

The methods of controlling the movement of the piston 10 employed in earlier techniques include monitoring motion times of the piston by means of microcontrolled circuits. The times to be monitored include: (i) resi-

dence time "t_o" of the piston 10 beyond a point R that is physically defined in its course of displacement, and this point is close to the end of the maximum course of displacement M possible to the piston 10, (ii) the time "t_c" of duration of the complete cycle, (iii) the time "t_{om}" corresponding to the maximum course of displacement M possible to the piston 10. The average voltage V_m applied to the motor 2 is incremented, if the time "t_o" is shorter than the desired time "t_{od}", and vice-versa. And the desired displacement "P" is maintained for supplying a determined cooling capacity (see figure 2).

The point M is very close to the valve plate 11, being typically at a distance of some dozens of micrometers, while the point R is located close to the valve plate 11, being typically at a distance of from 1 to 2 millimeters, a distance sufficient to avoid collision of the piston 10 with said plate 11.

According to the present invention, and on the basis of the above-cited information about the behavior of the piston 10, one may replace the microcontrolled control systems by passive control circuits, thus reducing the manufacture costs thanks to the low cost of the pieces, maintenance by low consumption of electricity.

Particularly, according to the present invention, one foresees a re-feed (or self-fed) electronic circuit 30, 40 that alters the amplitude of the course of displacement of the piston 10, with the same approach employed in other systems that are controlled by microcontrollers, but without the need for monitoring the cited times.

Thus, according to the present invention, the detection of the passage of the piston by the defined physical point R may be effected by some type of physical sensor S installed inside the compressor 1, be it of the contact, optical or inductive or any other type (see figure 3, in this case). However, this detection may also be effected by adding a magnetic disturbance to the voltage present in the terminals of the motor 2, this disturbance being created, for example, by a constructive detail of the magnetic circuit of the motor. This is the case of the construction of the circuit 40, figure 4.

According to two preferred solutions described here, the position sensor S may comprise the circuits 30, 40 illustrated in figure 3 and 4, which

include a position sensor S_p by direct contact and a position sensor L_s by inductive sensor, respectively, and which can effect the control automatically, without the need to employ a microcontrolled circuit.

The control system and method are carried out by means of a tiristor semiconductor device or bidirectional power switch T, which cyclically applies an electric voltage V to the motor L. The trigger circuit G (gate or inlet G) of this switch T is actuated by means of the position sensor Sp, Ls, which sends a signal that generates the angle of triggering said switch T, this signal causing a retardation time proportional to the discharge level of the capacitor Cy. The gate circuit G connected to the capacitor Cy, sends a voltage signal to the linear motor 2 for a longer or shorter time, for the purpose of adjusting the cooling capacity of said linear compressor 1.

Figure 5 illustrates the wave shape of the voltage V applied to the motor 2 and the stretches where the semiconductor device T does not conduct, as well as the wave shape of the current I.

As can be seen in figures 1, 3, and 4, according to the teachings of the present invention, the capacitor Cy is associated to the semiconductor device T, so that it will be associated between – and re-fed – the outlet S_G and the inlet G of the latter, and also in association with the switch S, which indicates the passage of the piston by the point R.

Figure 5 illustrates how this solution interferes with the voltage level V of the inlet of the motor L_m. Raising the voltage in the branch of the capacitor Cy (see stretch A in figure 5) is a function of the capacitance values of the Cy and Cx and of the resistance R_B. In this way, it is possible to adjust the circuit 30, 40 to varied constructions of the compressor 1, so that the semiconductor electronic device T can be adequately triggered (see stretch A' in figure 5, where the semiconductor T conducts).

The discharge velocity of the capacitor Cy is a function of the capacitance values of Cy, Cx and of the resistance values of R, R_T (see stretch B of the curve in figure 5), which should be designed in an adequate way, so that the triggering of the electronic device T will occur in an adequate way.

As can be seen in figure 3, a first preferred embodiment of the

movement-control system includes the circuit 30, which comprises a position sensor Sp constituted by an electromechanical switch that is directly driven by the piston 10 when the latter passes by the point R, resulting in alteration of operation of the semiconductor electronic device T.

In this embodiment, in order to trigger the semiconductor electronic device T through the respective gate, the capacitor Cy is charged by means of the resistance Rb up to a level Vb (threshold voltage of the transistor T_2), and remains in this state until the course of displacement of the piston 10 reaches the point R, where the position sensor Sp will close contact (see Sp = On in figure 5) for a short period of time and will discharge partly. The capacitor Cy, in the next semicycle, will cause the semiconductor electronic device T to enter with some delay, as may be inferred from the deformation of the voltage curve V at the point 23, illustrated in figure 2 (see also figure 3).

The residence time at zero level (or a sufficiently low level in the winding Lm of the motor 2, so that the latter will not operate) of voltage V will depend upon the time during which the contact of the position sensor Sp has remained closed and upon the value of Ri + Rt (for example, a thermostat). The values Ri + Rt should be such, that when Rt is at the condition of maximum resistance and the piston 10 reaches the point M, the capacitor Cy will be discharged at such a level, that the semiconductor electronic device T will not be triggered in the next semicycle.

According to a second preferred embodiment of the present invention, and as may be seen in the system 40 illustrated in figure 4, the sensor S is carried out by means of a sensor or inductive element L_i.

In this embodiment, the sensor Li detects (see Li = On in figure 5) the passage of the piston 10, causing the transistor T_2 to start conducting, discharging at least partly the capacitor Cy and actuating in a way analogous to that of the first preferred embodiment of the present invention.

As may be seen in figures 3 and 4, the circuits 30, 40 are self-fed and, therefore, they dispense with the use of an external feed source, which reduces the costs of manufacture and maintenance.

Further, the transistor T_1 closes the circuit in the two embodiments, so as to trigger the electronic device T, actuating as a bidirectional switch: now charging the capacitor Cy, now discharging it.

Since this is a self-fed circuit 30, 40, the present invention brings about, as an advantage, the possibility of dispensing with the use of an external feed source, in addition to resulting in a low consumption of electricity (in the milliamperes range) and in addition to enabling the replacement thereof in the event of a failure.

In order to implement the application of the systems described above, the present invention also foresees a method for controlling the movement of a piston 10 in a linear compressor 1 or any other fluid-pumping device 1. This method comprises the steps of:

- charging the capacitive element Cy by means of the resistive element R_b,
- monitoring the movement of the piston 10 by means of the position sensor S;
- maintaining the charge level of the capacitive element Cy until the position sensor S has detected the passage of the piston 10 by the point R, and
- discharging, at least partly, the capacitive element Cy.

Once the discharging step is finished, the capacitive element Cy is again charged, as may be seen in figure 5.

It is also an objective of the present invention to construct a fluid-pumping device 1, provided with the system for controlling the movement of the piston 10, to prevent the latter from bumping into the valve plate 11.

Thus, according to the present invention and to its teachings, collision of the piston 10 with the valve plate 11 may be avoided. The intermediate situations will serve as a control over the capacity of the compressor 1.

The system and method of the present invention enable one to estimate, at each cycle, the oscillation amplitude of the piston 10 much more precisely, enabling the electronic control to react for compensating the varia-

tions in the cooling capacity (in the case of application in compressors), which are slow variations, maintaining the average amplitude of the course of oscillation of the piston 10 at the desired value and equal to P. This system and method also enables rapid reactions of the electronic control for compensating shape variations in the operation conditions caused by fluctuations in the feed voltage, and these corrections should be imposed at each oscillation cycle, so as to correct the amplitude of the stroke of the piston 10 in the final portion of its path, after passing by the physical reference point R.

The system and method of the present invention result in the advantage of a rapid reaction, with corrections at each cycle, without the need for estimates based on the voltage and current imposed on the motor 2, and without mistakes due to secondary variables such as temperature, the construction of the motor 2 and the displacement of the middle point of oscillation of the piston due to the average difference in pressure between the faces 8, 9 of the piston 10.

The present invention enables one to implement an effective control over the course of displacement of the piston 10, independently of the required cooling capacity, whereby one can prevent the piston 10 from bumping against the valve plate 11, even in the presence of rapid disturbances caused by the natural fluctuation of the voltage in the commercial network of electric energy.

Preferred embodiments having been described, it should be understood that the scope of the present invention embraces other possible variations, being limited only by the contents of the accompanying claims, which include the possible equivalents.